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FORECASTING SHORT-TERM MOVEMENT AND INTENSIFICATION OF TROPICAL CYCLONES USING PATTERN-RECOGNITION TECHNIQUES

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19. ABSTRACT Weather forecasters recognize patterns within meteorological data fields and associate these patterns with a response of observed weather events, such as rain or hail. Two pattern recognition techniques, a linear statistical technique (correlation analysis) and a nonlinear neural network technique (back propagation), were tested to recognize patterns within the surrounding wind and height fields of tropical cyclones and to relate these patterns to short-term (24 hours into the future) movement and intensification of the cyclones.

Two independent databases were obtained for tropical cyclones occurring within the western North Pacific region. The developmental database represented 292 cases of tropical cyclones and associated fields from 1978 to 1987; the test database contained 54 cases from 1988 to 1989. Gridded field data (5x5 with a 300 nm grid spacing) consisted of five upper-air levels of geopotential height and u and v components of the wind centered on the tropical cyclone. The forecast ability of both pattern recognition techniques was compared to that of persistence, the forecasters at the Joint Typhoon Warning Center (JTWC), and three objective forecast techniques employed at JTWC.

The neural network technique, back propagation, predicted short-term intensification more accurately than the forecasters at JTWC and persistence; the correlation analysis method was not as accurate. Both pattern-recognition techniques forecast short-term movement better than persistence and comparably to the forecasters at JTWC; however, both techniques were biased toward forecasting persistent movement. Combining the forecasts of JTWC and associated objective aids with the input data of the back propagation technique improved the overall results, apparently selecting the best forecast for the given synoptic situation.

The ability of back propagation to forecast short-term intensification and movement of tropical cyclones was very promising, considering the coarse distribution of the data. Future work should be focused on improving the back propagation technique because the technique is ideal for operational forecasting of weather events, requiring minimal computer storage and execution time.

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1. INTRODUCTION

Since the inception of the Joint Typhoon Warning Center (JTWC), Nimitz Hill, Guam, in 1947, one of the tools used to forecast tropical cyclone movement and intensification is the analysis of prognostic and diagnostic height and wind fields. Over the years, forecasters have developed conceptual models and forecast aids based on the response of the tropical cyclones to perceived patterns within the surrounding height and wind fields. For example, Weir[1] developed an empirical technique that forecasts rapid northeastward acceleration of tropical cyclones based on patterns within the upper-level westerlies. Matsumoto[2] used the position of the tropical cyclone relative to the 500 mb subtropical ridge to develop a statistical forecast aid currently used as guidance at JTWC.

The purpose of this study was to develop automated techniques to relate short-term (24 hours into the future) movement and intensification of tropical cyclones to recurring patterns within the surrounding height and wind fields. Two techniques were used to identify patterns: a linear statistical technique (correlation analysis) and a non-linear neural network technique (back propagation).

Currently at JTWC, an analog technique, called Typhoon Analog (TYAN), uses a 30-year climatology database to provide guidance of tropical cyclone movement (1989 Annual Tropical Cyclone Report[3]). The aid requires the manual input of the following data: date; past 12 hr position current position; current intensity; longitude along the 35 degree parallel of the closest 700 mb trough located to the northwest of the tropical cyclone; and the latitude of the 700 mb ridge located to the north of the tropical cyclone. The aid yields three outputs: 1) a mean track of the selected tropical cyclones that were categorized as recurring; 2) a mean track of the selected tropical cyclones that travelled westward throughout their duration; and 3) a mean of all selected tropical cyclone tracks regardless of classification. TYAN has not been updated since 1976 to include more current information and does not include synoptic information above 700 mb. TYAN is not one of the most accurate objective aids used at JTWC.

JTWC's intensity forecasts of the maximum sustained winds are based solely on the interpolation of satellite imagery intensity estimates[4]. Past studies have not provided an adequate correlation of intensification with surrounding height and wind fields.

2. DATA

Upper-air soundings from 30 stations located throughout the western North Pacific region (Figure 1) were collected from 1978 to 1989. Additional station reports were available, but these 30 had relatively high reliability and provided adequate coverage of Japan and South Korea. Soundings

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1. Weir, R.C. (1982): Predicting the Acceleration of Northward-moving Tropical Cyclones Using Upper-Tropospheric Winds. NAVOCEANCOMCEN/JTWC Technical Note 82-2, 40 pp.

2. Matsumoto, C.R. (1984): A Statistical Method for One to Three Day Tropical Cyclone Track Prediction. Atmospheric Science Paper 379, NEPRF N00014-83-k-002, NSF ATM-8214041, Department of Atmospheric Science, Colorado State University, Fort Collins, 201 pp.

3. 1989 Annual Tropical Cyclone Report, U.S. Naval Oceanography Command Center, Guam, 216 pp.

4. Dvorak, V.F. (1984): Tropical Cyclone Intensity Analysis Using Satellite Data. NOAA Technical Report NESDIS 11, U.S. Department of Commerce, National Oceanic and Atmospheric Administrations, National Earth Satellite Service, Washington D.C., 20233, 46 pp.

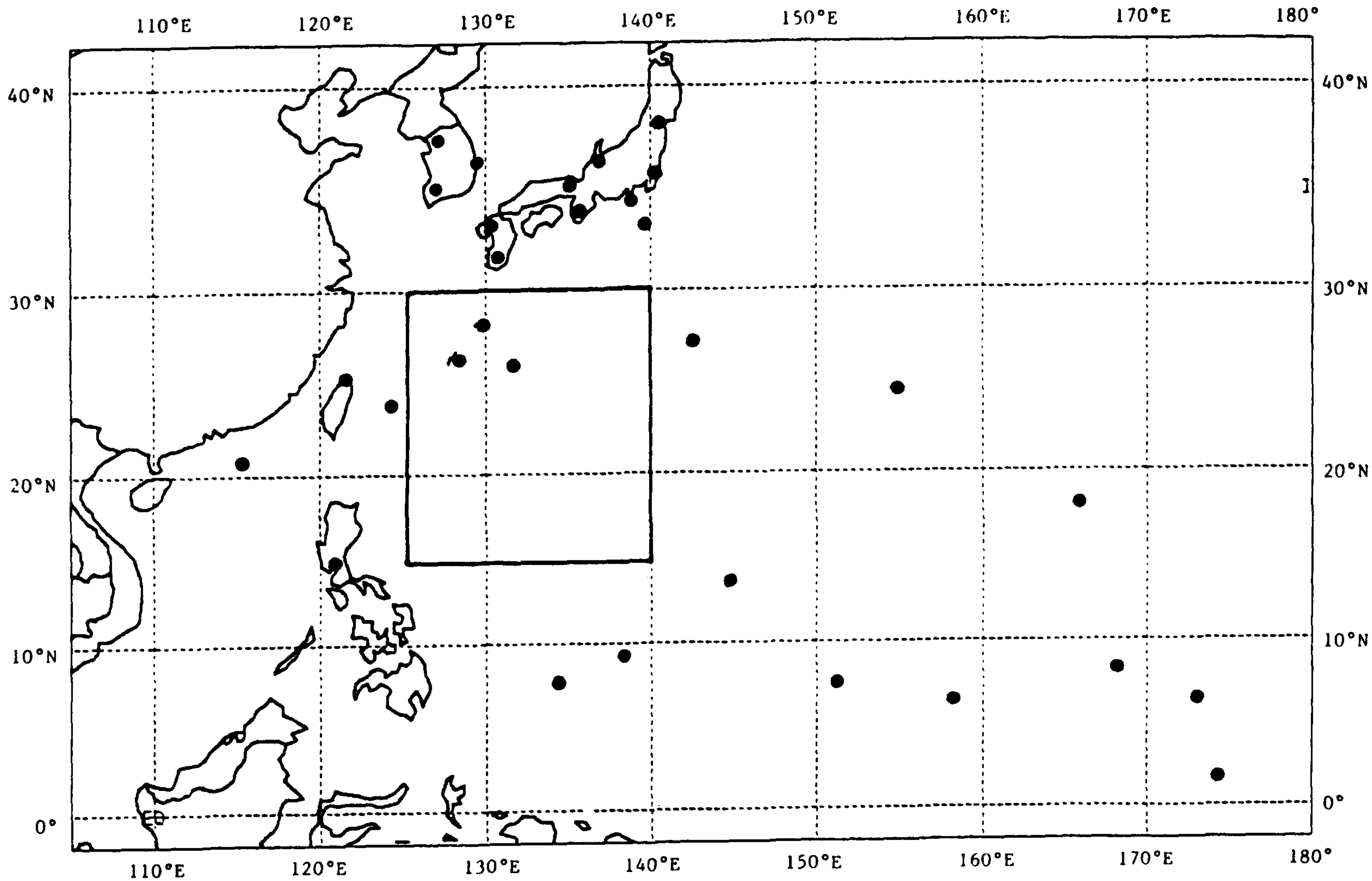

Figure 1 Distribution of the 30 upper-air stations in the western North Pacific region used to define height and wind fields surrounding tropical cyclones. Tropical cyclones tracking within a 15° x 15° area bounded by 15° N to 30° N and 125° E to 140° E were used to select fields for the pattern recognition study.

from China were not included in this study because JTWC did not receive these reports. The data was divided into two databases: a developmental database representing upper-air soundings from 1978 to 1987 and an independent test database representing 1988 and 1989. Only the winds (speed and direction) and heights of five mandatory levels were recorded from the soundings: 700, 500, 400, 300, and 200 mb (roughly representing 3100, 5800, 75000, 9400 and 12,400 m, respectively). Typically, the 700 mb data represents the low level, 500 and 400 mb the mid levels and 300 and 200 mb the upper levels of a tropical cyclone's environment.

Tropical cyclone tracks, consisting of six-hourly positions and intensities as determined by JTWC (see 1989 Annual Tropical Cyclone Report for details on their positioning and intensity estimate procedures) were obtained from 1978 to 1989. Only tropical cyclones with an intensity of 34 knots or greater (tropical storm intensity or greater) were considered in this study.

3. DATA PREPARATION

Heights at the five levels were analyzed for spurious points for each of the 30 stations. Using the entire database from 1978 to 1989, the mean and standard deviation of heights at the five levels were calculated for each of the 30 stations. For cases with a sequence of three observations spaced 24 hours apart, data were determined to be spurious when the height of a given level was greater than one standard deviation from the two surrounding observations. For cases with an incomplete record of heights, anomalous data were identified when the value exceeded two standard deviations from the mean height for that particular station. Inconsistent height and corresponding wind speed and direction were eliminated. Height and wind field data were then combined with chronologically corresponding tropical cyclone tracks.

Back propagation required the values of input data to be within 0 and 1. It is recommended that numbers range from 0.1 to 0.9 to help the weights function properly. The field data were normalized using the maximum and minimum values of each 5 x 5 gridded data field.

Data were limited in space and time to restrict the forecast domain. Van den Dool[5] states that analogs forecast weather best when using a limited area approach. Only 0000 UTC data were used, to eliminate diurnal trends of synoptic features and because most tropical island stations reported only at 0000 UTC. The effects of land and the variation of Coriolis force on the tropical cyclone (that is, beta motion, see Elsberry et al[6], and Holland[7]), were minimized by geographically limiting the data to those tropical cyclones between 15 and 30 degrees north latitude and 125 and 140 degrees east longitude (Figure 1). Only data from June to December were analyzed, to decrease the size of the stored databases.

Because of the discontinuity of wind direction at 360 degrees, the u and v components, respectively were calculated. The height and wind fields were objectively analyzed into gridded fields using the Cressman technique (see Thomason,[8] for details). The resulting fields were 5 x 5 grids centered on the

5. Van Den Dool, H.R. (1989): A New Look at Weather Forecasting Through Analogues. Mon. Wea. Rev. 117: 2230-2246.

6. Elsberry, R.L., Editor (1987): A Global View of Tropical Cyclones. Report of International Workshop on Tropical Cyclones, Bangkok, Thailand, Nov. 25 - Dec. 5, 1985, ONR, 185 pp.

7. Holland, G.R. (1983): Tropical Cyclone Motion: Environmental Interaction, Plus a Beta Effect. Sci., 40: 328-342.

8. Thomason, L.W. (1988): Private Communication.

quadrant of motion (NE, SE, SW and NW). The distributions of the past motion relative to the future quadrant of motion from 1978 to 1987 and from 1988 to 1989 are presented in Table 1. Persistence of motion dominated the data distributions with one exception: the dominant future short-term motion

Table 1. Distribution of past quadrant of motion (observed motion during the previous 12 hours) with respect to future (24 hour motion occurring from the time of the forecast) quadrant of motion.

DEVELOPMENTAL DATABASE (1978 - 1987)

PAST MOTION	FUTURE MOTION				
	NE	SE	SW	NW	TOTAL
NE	58	1	1	7	67
SE	0	3	1	1	5
SW	1	2	4	12	19
NW	28	0	12	161	201
TOTAL	87	6	18	181	292

TEST DATABASE (1988 - 1989)

PAST MOTION	FUTURE MOTION				
	NE	SE	SW	NW	TOTAL
NE	12	0	0	1	13
SE	0	0	0	0	0
SW	0	0	2	7	9
NW	5	0	4	23	32
TOTAL	17	0	6	31	54

associated with tropical cyclones traveling southwestward was northwest, not persistence.

Changes in intensity over a 24-hour period were based on T-numbers (Dvorak, 1984) rather than maximum sustained wind speed, due to the nonlinear relationship between T-numbers and maximum sustained winds (Table 2). Table 3 shows 1) the distribution of future intensification (the change in intensity during the 24 hours following the forecast) with respect to intensification during the past 24 hours, 2) quadrant of motion during the previous 12 hours, and 3) the intensity of maximum sustained wind at the time of the forecast.

Persistence occurred when the past intensification remained unchanged within the short-term future. If persistence were forecast for the test database, 26 percent of the cases would verify within +/- 0 T-number difference (the magnitudes of past and future intensity change were equivalent), and 87 percent would verify within +/- 1 T-number difference (the magnitude of the future intensity change was

Table 2. Relationship between Dvorak's (1984) T-number classification and maximum sustained winds. JTWC used aircraft reconnaissance data when reporting intensities of tropical cyclones greater than 140 knots. Aircraft reconnaissance was stopped in August, 1987.

T-NUMBER	CURRENT INTENSITY (knots)
1.0	25
1.5	25
2.0	30
2.5	35
3.0	45
3.5	55
4.0	65
4.5	77
5.0	90
5.5	102
6.0	115
6.5	127
7.0	140

within 1 T-number of the past intensity change value). Similar trends were observed from 1978 to 1987.

Collectively, the modal frequencies of intensification associated with each of the four quadrants of motion during the past 12 hours represented 23 percent of the 292 cases from 1978 to 1987 (Table 3). If the frequencies within 1 T-number of the four modal points were included, 74 percent of the developmental database would be included. If the same relationship of the modal distribution observed

Table 3. Distribution of future intensity change (+24 hr) with respect to past quadrant of movement (motion during the preceding 12 hours), past intensity change (intensification during the preceding 24 hours) and current intensity. Intensification is based upon Dvorak's (1984) T-number classification.

DEVELOPMENTAL DATABASE (1978 - 1987)

PAST MOTION	FUTURE CHANGE IN INTENSITY (T-NUMBER)											
	<-2	-2	-1.5	-1	-0.5	0	0.5	1	1.5	2	>2	TOTAL
NE	0	5	7	19*	15	9	4	7	0	1	0	67
SE	0	0	0	3*	0	0	0	2	0	0	0	5
SW	0	0	1	4	1	3	4*	4	1	1	0	19
NW	1	2	8	41	38	10	42*	41	11	3	4	201
TOTAL	1	7	16	67	54	22	50	54	12	5	4	292

Table 3 Continued

PAST INTENSITY CHANGE (T-NUMBER)	FUTURE CHANGE IN INTENSITY (T-NUMBER)											
	<-2	-2	-1.5	-1	-0.5	0	0.5	1	1.5	2	>2	TOTAL
<-2	0	0	0	1	0	0	0	0	0	0	0	1
-2	0	0	0	0	1	0	0	0	0	0	0	1
-1.5	0	0	0	0	1	0	1	2	0	0	0	4
-1	0	2	8	18	15	2	2	2	0	0	0	49
-0.5	0	1	3	17	10	5	2	1	0	0	0	39
0	0	2	1	3	6	4	0	1	1	0	0	18
0.5	0	1	1	9	11	6	14	12	1	1	0	56
1	1	0	3	10	7	4	25	21	5	2	2	80
1.5	0	1	0	6	0	0	4	9	4	2	1	27
2	0	0	0	2	2	1	2	4	1	0	1	13
<2	0	0	0	1	1	0	0	2	0	0	0	4
TOTAL	1	7	16	67	54	22	50	54	12	5	4	292

CURRENT INTENSITY (KNOTS)	FUTURE CHANGE IN INTENSITY (T-NUMBER)											
	<-2	-2	-1.5	-1	-0.5	0	0.5	1	1.5	2	>2	TOTAL
35	0	0	0	2	2	1	5	8*	0	1	0	19
40-45	0	0	2	5	1	1	4	7*	4	2	0	26
50-55	0	0	2	6	4	0	10	11*	2	0	2	37
60-65	0	0	0	1	6	4	11*	8	3	0	1	34
70-75	0	0	1	7	6	3	8*	7	0	1	0	33
80-85	0	1	4	7	7	8*	4	3	1	1	1	37
90-95	0	2	1	6	9*	1	2	2	1	0	0	24
100-105	0	2	1	6*	5	0	1	3	1	0	0	19
110-115	0	1	2	6*	4	1	4	2	0	0	0	20
120-125	1	0	2	10*	5	3	0	2	0	0	0	23
130-135	0	0	0	4*	4	0	0	1	0	0	0	9
140-145	0	1	0	4*	1	0	1	0	0	0	0	7
150-155	0	0	1	2*	0	0	0	0	0	0	0	3
160-165	0	0	0	1*	0	0	0	0	0	0	0	1
TOTAL	1	7	16	67	54	22	50	54	12	5	4	292

* modal frequency with respect to future change in intensity; if two apparent modes, selected mode with greatest neighboring frequencies.

TEST DATABASE (1978 - 1987)

PAST MOTION	FUTURE CHANGE IN INTENSITY (T-NUMBER)											
	<-2	-2	-1.5	-1	-0.5	0	0.5	1	1.5	2	>2	TOTAL
NE	0	0	2	1*	3	1	3	1	2	0	0	13
SE	0	0	0	0*	0	0	0	0	0	0	0	0
SW	0	0	0	0	1	2	2*	3	0	1	0	9
NW	0	0	0	3	8	3	8*	6	1	2	1	32
TOTAL	0	0	2	4	12	6	13	10	3	3	1	54

Table 3 Continued

PAST INTENSITY CHANGE (T-NUMBER)	FUTURE CHANGE IN INTENSITY (T-NUMBER)											
	<-2	-2	-1.5	-1	-0.5	0	0.5	1	1.5	2	>2	TOTAL
<-2	0	0	0	0	0	0	0	0	0	0	0	0
-2	0	0	0	0	0	0	0	0	0	0	0	0
-1.5	0	0	0	0	0	0	0	0	0	0	0	0
-1	0	0	0	2	1	0	0	0	0	0	0	3
-0.5	0	0	2	1	0	0	2	0	0	0	0	5
0	0	0	0	0	2	0	0	0	1	0	0	2
0.5	0	0	0	0	6	1	5	1	1	1	0	13
1	0	0	0	1	2	3	5	6	2	2	0	21
1.5	0	1	0	0	0	2	1	0	1	1	1	6
2	0	0	0	0	1	0	0	2	0	0	0	3
<2	0	0	0	0	0	0	0	1	0	0	0	1
TOTAL	0	0	2	4	12	6	13	10	3	3	1	54

CURRENT INTENSITY (KNOTS)	FUTURE CHANGE IN INTENSITY (T-NUMBER)											
	<-2	-2	-1.5	-1	-0.5	0	0.5	1	1.5	2	>2	TOTAL
35	0	0	0	0	2	1	5	8*	0	1	0	7
40-45	0	0	0	0	1	1	4	7*	4	2	0	12
50-55	0	0	0	0	4	0	10	11*	2	0	2	7
60-65	0	0	0	0	6	4	11*	8	3	0	1	4
70-75	0	0	0	0	6	3	8*	7	0	1	0	2
80-85	0	0	0	0	7	8*	4	3	1	1	1	3
90-95	0	0	0	2	9*	1	2	2	1	0	0	7
100-105	0	0	1	0	5	0	1	3	1	0	0	1
110-115	0	0	0	1*	4	1	4	2	0	0	0	5
120-125	0	0	1	1*	5	3	0	2	0	0	0	6
130-135	0	0	0	0*	4	0	0	1	0	0	0	0
140-145	0	0	0	0*	1	0	1	0	0	0	0	0
150-155	0	0	0	0*	0	0	0	0	0	0	0	0
160-165	0	0	0	0*	0	0	0	0	0	0	0	0
TOTAL	0	0	2	4	12	6	13	10	3	3	1	054

* location of modal frequencies calculated from 1978 to 1987 data

within the developmental database were forecast for the test database, 20 percent of the intensity forecasts would verify within +/- 0 T-number and 76 percent would verify within +/- 1 T-number.

Persistence of intensification and model distribution trends described above represent "no-skill" forecasts; no understanding of the current synoptic situation is required to issue a forecast. The ability of these simple no-skill forecasting techniques represent the minimum acceptable level of performance and, therefore, will be used as the baseline to compare the predictive skill of the pattern recognition techniques.

Similarly, persistence of motion represents the no-skill forecast of tropical cyclone motion. In addition to comparing motion forecasts to persistence, the performance of the pattern recognition techniques will be compared to the accuracy of forecasters at JTWC and their three most accurate objective aids.

4. METHODS OF ANALYSES

The ability of the neural network and statistical techniques to predict the motion of tropical cyclones was compared to that of persistence, the forecasters at JTWC and their three most accurate objective forecast aids. The objective motion forecast aids are the dynamical aid, One-Way Tropical Cyclone Model (OTCM) of Hodur and Burk[9]; the statistical aid, the Colorado State University Model (SCUM) of Matsumoto[2]; and half-persistence and climatology (HPAC) (1989 Annual Tropical Cyclone Report).[3] Tsui and Miller[10] provide a detailed analysis of performance of these aids and others used at JTWC.

The accuracy of the pattern recognition techniques to predict short-term intensification was compared to that of the forecasters at JTWC, persistence of observed intensification trends the the "no skill" forecasts based on the climatology of modal distributions described in the previous section. Forecasts based solely on Dvorak's technique, issued by the satellite analysts stationed at JTWC, were not obtained for this study.

4.1 Correlation Analysis

The correlation analysis technique used in this study was fashioned after Lund[11,12]. Initially, the Lund technique was used to identify the common types of fields occurring within the western North Pacific region; however, there were too few common field types to compare to the test case fields. This led to low correlation values of a test case field to the best matched common field type. The technique was modified so that the correlation of each test case field (54 cases) to each

9. Hodur, R.M. and S.D. Burk (1978): The Fleet Numerical Weather Central Tropical Cyclone Model: Comparison of Cyclonic and One-Way Interactive Boundary Conditions. 106: 1665-1671.

10. Tsui, T.L. and R.J. Miller (1986): Evaluation of JTWC Tropical Cyclone Objective Forecast Aids (1978-85), Naval Environmental Prediction Research Facility Technical Report, TR86-05, 44 pp.

11. Lund, I.A. (1972): Climatology as a Function of Map Type, Environmental Research Papers No. 391, AFCRL-72-0173, 14 pp. AD740855.

12. Lund, I.A. (1963): Map-Pattern Classification by Statistical Methods, Appl. Meteorol., 2: (No. 1), 56-65.

of the fields within the developmental database (292 cases) was calculated.

To further improve the performance of correlation analysis, several techniques were applied that were similar to techniques used by forecasters at JTWC. First, the data fields were divided into four quadrants (see Figure 2 for the two configurations presented in this paper). The central grid point was omitted because a vortex was not bogused into the objective analysis scheme. If the central grid point had been included, the point would have influenced the four correlation calculations per field. Configuration A emphasizes the northeast/southwest and northwest/southeast orientations, and configuration B emphasizes the north/south and east/west orientations about the tropical cyclone. Test case data were compared only to 1978 and 1987 data that had similar tropical cyclone motions. When the correlation between quadrants was above a given threshold (typically 0.90), the motion/intensification associated with the developmental database quadrant was recorded. The dominant motion/intensification associated with the best correlated quadrants was compared to that of the test case. A match occurred when the two motions were the same or if the intensifications were within a specified range from each other. A miss was assumed when no fields were well correlated to the test case.

To improve the ability of correlation analysis to forecast intensification, information of the current intensity needed to be considered in addition to the techniques already employed. Cases from the developmental database were used in the correlation analysis method when the current intensity of the tropical cyclone was within a specified range from the current intensity of the test case. For example, when the developmental case listed a current intensity of 45 knots and the test case intensity 125 knots, the developmental case would not be used if the intensity range were specified as 50 knots. Three intensity ranges were tested: 100, 50 and 25 knots.

4.2 Back Propagation

The primary applications of neural networks are for situations where only a few decisions are required from a massive amount of data or situations where a complex mapping must be learned.[13] Simpson discusses neural networks and back propagation in considerable detail and provides a thorough list of references. In general, back propagation is a "heterassociative, function-estimation artificial neural system that stores arbitrary analog spatial pattern pairs using a multilayer gradient descent error-correction encoding algorithm."[13] Back propagation learns in a supervised setting, that is, for each set of training input provided, an output is required.

To improve the performance of back propagation, information of the past motion was incorporated. Four neural networks were trained on data sets divided by the four quadrants of past motion: northeast, southeast, southwest and northwest. Various neural network structures were tested, but, unless stated, the structure consisted of 25 input nodes, a single 25-node that with optimum training sets, neural networks are capable of performing at outstanding levels. Unfortunately, with meteorology and synoptic fields, determining and acquiring optimum

13. Simpson, P.K. (1990): Artificial Neural Systems: Foundations, Paradigms, Applications and Implementations, Pergamon Press, 209 pp.

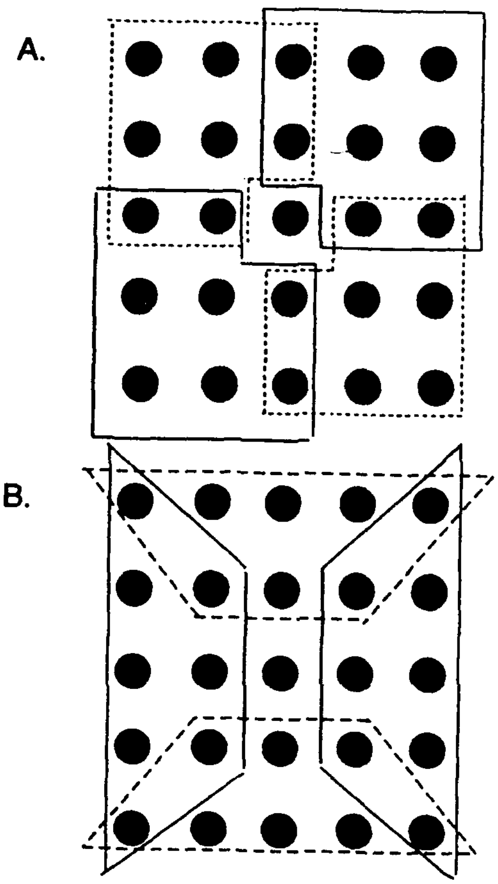

Figure 2 Two pattern schemes used to separate wind and height fields into four quadrants for the correlation analysis technique. The overlapping areas in configuration A emphasized east/west orientations about the tropical cyclone, whereas the placement of the quadrants highlights the northeast, southeast, southwest and northwest directions. In configuration B, the overlapping areas are oriented northeast/southwest and northwest/southeast to the tropical cyclone, and the quadrants are situated north, east, south and west of the center of the vortex.

hidden layer and an appropriate number of output nodes based on the phenomena to be forecast. For example, forecasting the quadrant of motion required four output nodes and forecasting intensification required 11 output nodes.

5. RESULTS

In the sections that follow, the performance of both pattern recognition techniques represents the best forecast ability of each technique when using patterns determined from single variable fields. For example, the back propagation method best forecasts the quadrant of motion when using the geopotential height fields at 300 and 200 mb. The back propagation technique issued separate forecasts based on pattern information recognized within 15 single variable fields (three parameters at five upper-air levels). The best performance of the correlation technique was selected from 30 separate forecasts because two schemes were used to divide the 15 single variable data fields into quadrants (Figure 2). The best performance was determined from the overall accuracy of the forecasts issued for 1988 to 1989 data. The same field data were used in further analysis of the forecast technique.

Summaries of forecasts from the pattern recognition techniques using single and multiple variable fields and those issued by JTWC and their three most reliable objective aids from 1978 to 1987 and from 1988 to 1989, are recorded in the appendixes.

5.1 Forecasting Short-Term Quadrant of Motion

In overall forecast accuracy for 1988 to 1989, both pattern-recognition techniques were comparable to the forecasters at JTWC (Figure 3 and Appendix A). All six forecast techniques, correlation analysis, back propagation, JTWC and three objective aids used operationally at JTWC, performed more accurately than persistence. HPAC was the best forecast technique for 1988-89; however, HPAC's performance during 1978 to 1987 was less impressive (Appendix A).

The influence of the tropical cyclone's past motion on the accuracy of the forecast techniques was examined. None of the techniques forecast the motion of tropical cyclones tracking with a northward component better than persistence (Figure 4). Correlation analysis and back propagation were not skilled at predicting tropical cyclones moving either northwestward or northeastward (Figures 5 and 6). The overall ability of the pattern recognition techniques to predict motion was a result of accurate forecasts for tropical cyclones tracking southwestward (Figure 7).

A false start is defined as a forecast that predicts a change in the direction (quadrant) of motion from the current movement but persistence actually occurs. Back propagation and correlation analysis experienced false start rates near 8 percent similar to JTWC (Figure 8 and Appendix A). OTCM produced the greatest number of false starts, particularly for tropical cyclones traveling northeastward (Figures 8, 9 and 10).

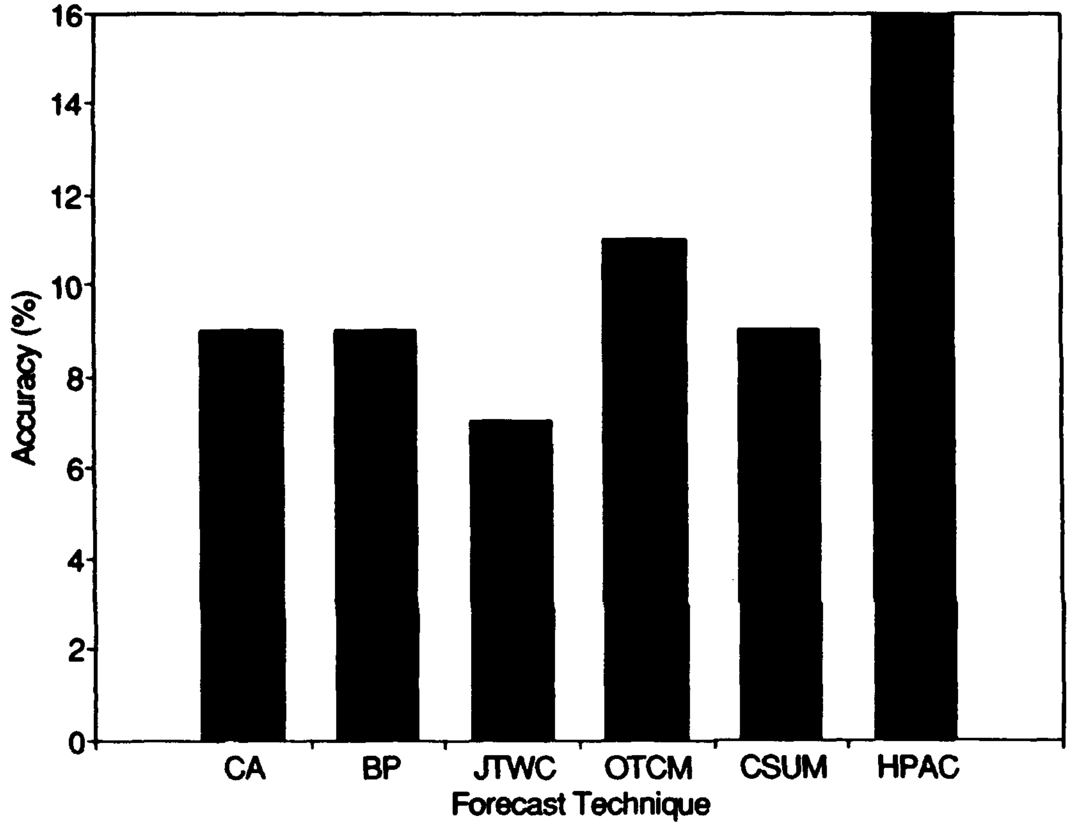

Figure 3 Overall forecast accuracy of the quadrant of motion relative to the forecast ability of persistence. For example, both correlation analysis (CA) and back propagation (BP) forecast the quadrant of motion more accurately than persistence by 8%. JTWC represents forecasts issued by the Joint Typhoon Warning Center (JTWC), Guam; and OTCM, CSUM and HPAC are the results of the three most reliable objective motion forecast aids employed at JTWC.

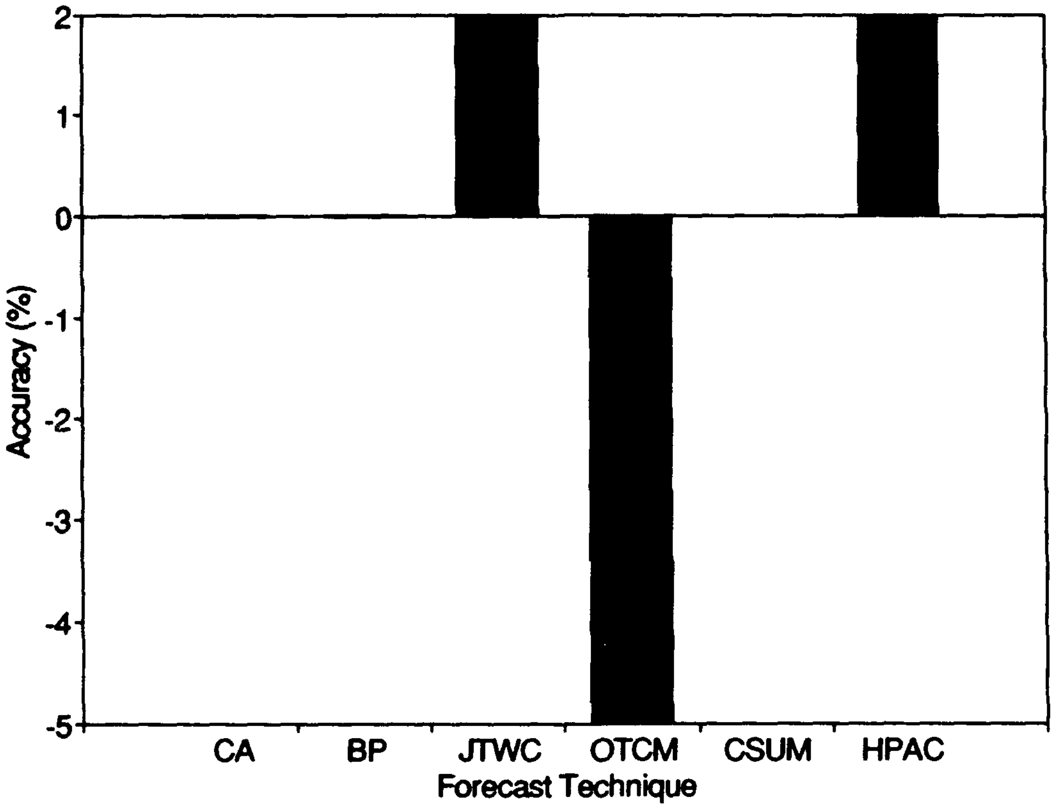

Figure 4 Forecast accuracy of the quadrant of motion for tropical cyclones tracking with a northward component at the time of the forecast. Accuracies are relative to the forecast ability of persistence. For example, correlation analysis (CA) and back propagation (BP) produced the same number of accurate forecasts as persistence. JTWC represents forecasts issued by the Joint Typhoon Warning Center (JTWC), Guam; and OTCM, CSUM and HPAC are the results of the three most reliable objective motion forecast aids employed at JTWC.

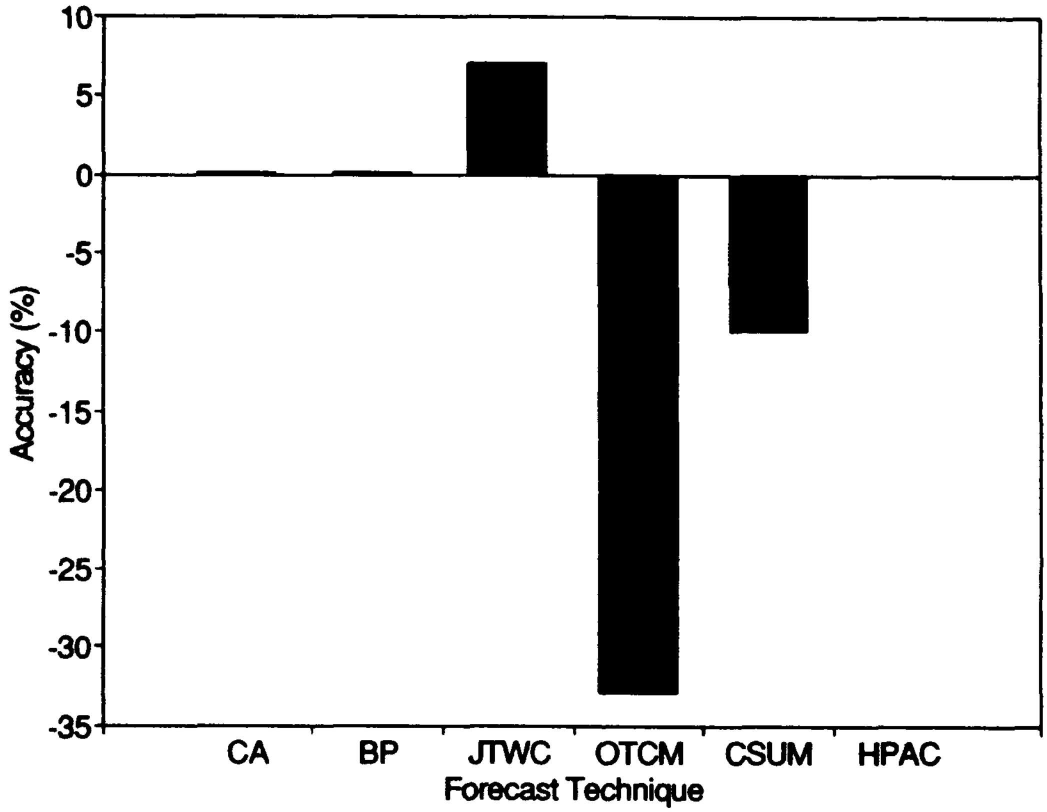

Figure 5 Forecast accuracy of the quadrant of motion for tropical cyclones tracking northeastward at the time of the forecast. Accuracies are relative to the forecast ability of persistence. For example, correlation analysis (CA) and back propagation (BP) produced the same number of accurate forecasts as persistence. JTWC represents forecasts issued by the Joint Typhoon Warning Center (JTWC), Guam; and OTCM, CSUM and HPAC are the results of the three most reliable objective motion forecast aids employed at JTWC.

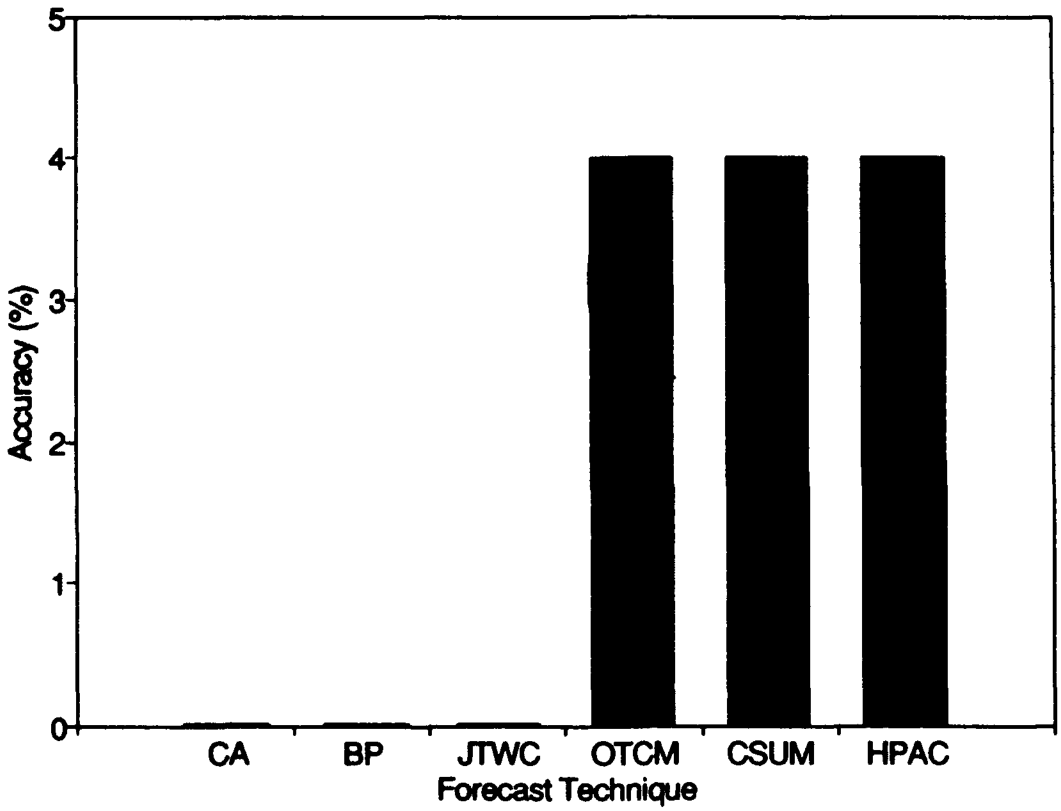

Figure 6 Forecast accuracy of the quadrant of motion for tropical cyclones tracking northwestward at the time of the forecast. Accuracies are relative to the forecast ability of persistence. For example, correlation analysis (CA) and back propagation (BP) produced the same number of accurate forecasts as persistence. JTWC represents forecasts issued by the Joint Typhoon Warning Center (JTWC), Guam; and OTCM, CSUM and HPAC are the results of the three most reliable objective motion forecast aids employed at JTWC.

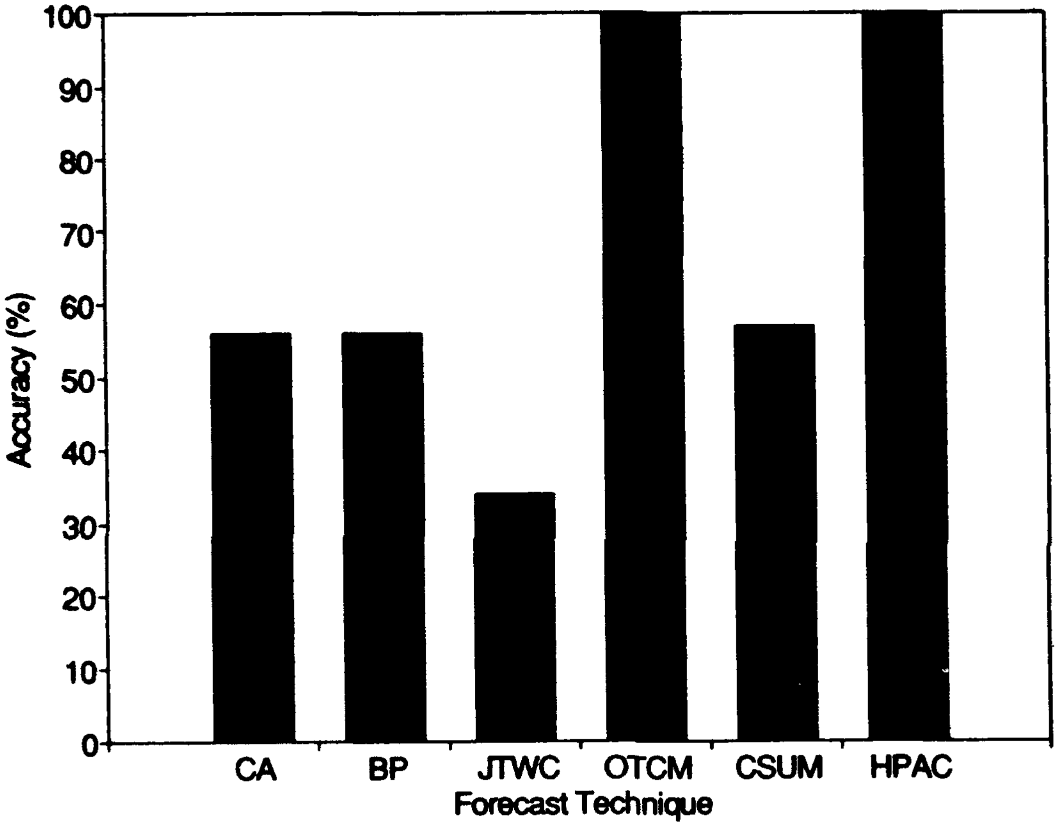

Figure 7 Forecast accuracy of the quadrant of motion for tropical cyclones tracking southwestward at the time of the forecast. Accuracies are relative to the forecast ability of persistence. For example, correlation analysis (CA) and back propagation (BP) forecast more accurately than persistence by 55 percent. JTWC represents forecasts issued by the Joint Typhoon Warning Center (JTWC), Guam; and OTCM, CSUM and HPAC are the results of the three most reliable objective motion forecast aids employed at JTWC.

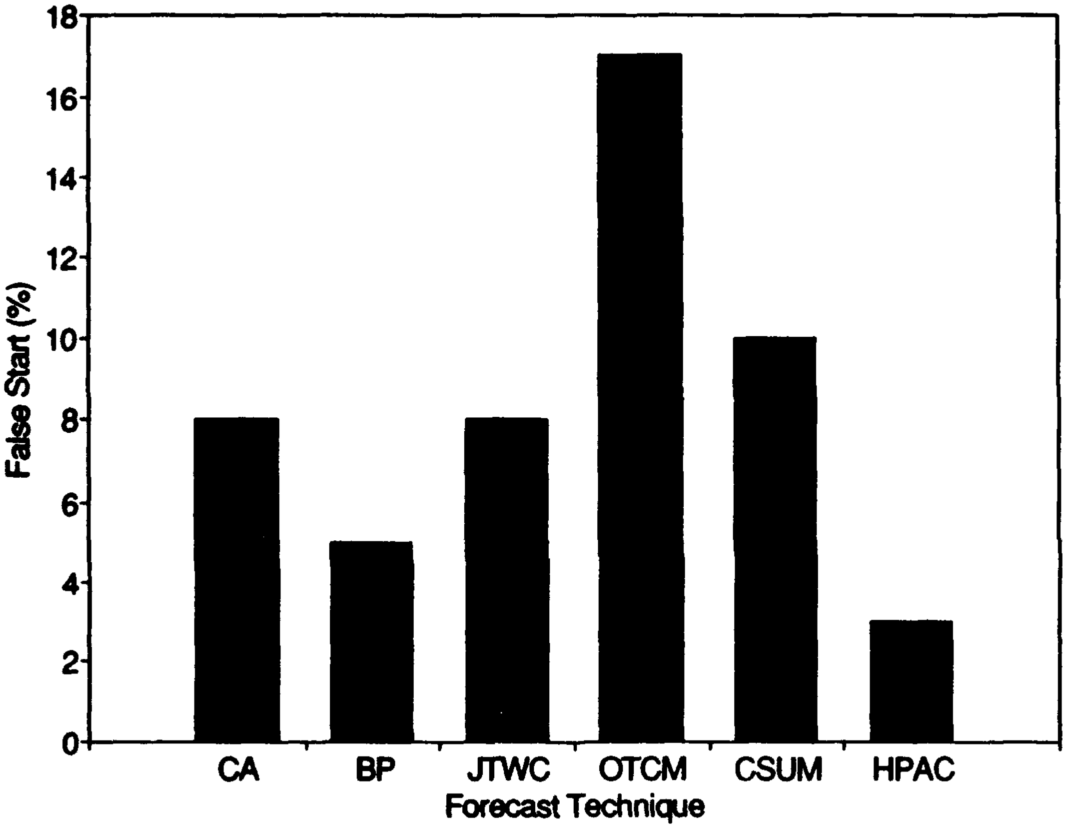

Figure 8 Percentage of forecasts of persistent events that were false starts. A false start occurs when there is a forecasted change in the direction of motion but persistence occurs. For example, of the persistent events, correlation analysis (CA) and back propagation (BP) incorrectly forecast a change in the quadrant of motion 8 percent and 5 percent of the time, respectively. JTWC represents forecasts issued by the Joint Typhoon Warning Center (JTWC), Guam; and OTCM, CSUM and HPAC are the results of the three most reliable objective motion forecast aids employed at JTWC.

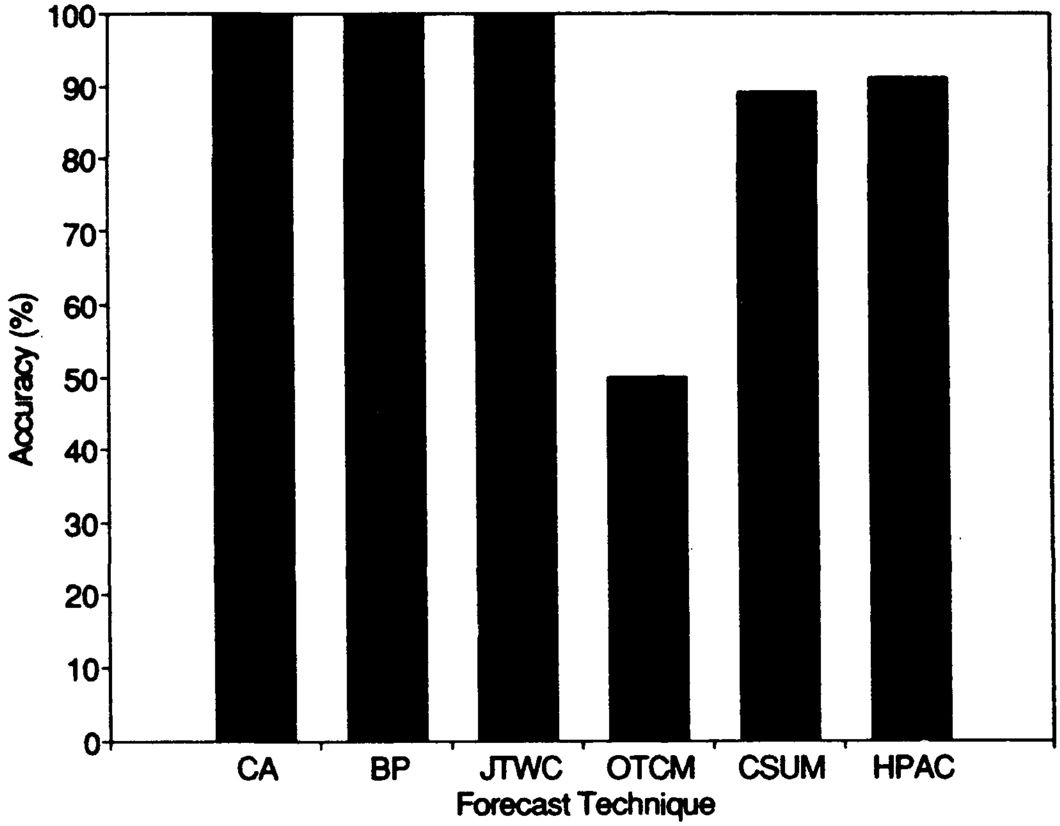

Figure 9 Forecast accuracy of the quadrant of motion for tropical cyclones tracking northeastward. For example, both correlation analysis (CA) and back propagation (BP) correctly forecast northeastward persistent motion for every event. JTWC represents forecasts issued by the Joint Typhoon Warning Center (JTWC), Guam; and OTCM, CSUM and HPAC are the results of the three most reliable objective motion forecast aids employed at JTWC.

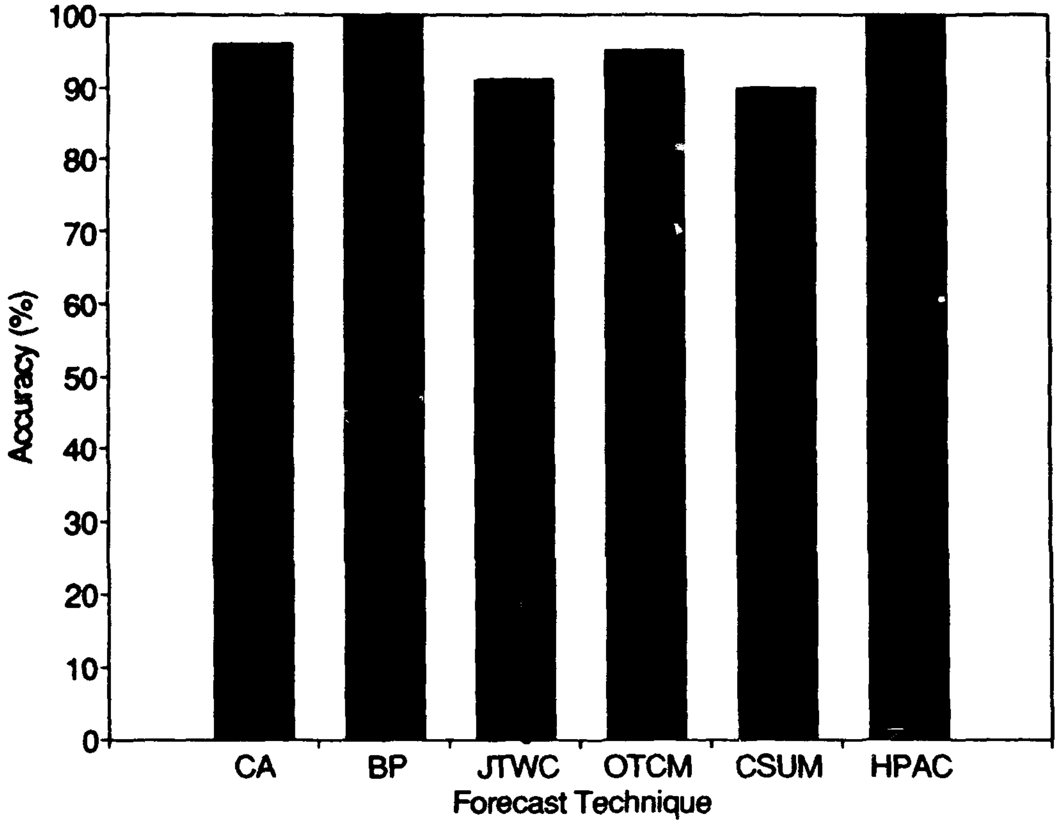

Figure 10 Forecast accuracy of the quadrant of motion for tropical cyclones tracking northwestward. For example, correlation analysis (CA) and back propagation (BP) correctly forecast northwestward persistent motion 96 percent and 100 percent of the time, respectively. JTWC represents forecasts issued by the Joint Typhoon Warning Center (JTWC), Guam; and OTCM, CSUM and HPAC are the results of the three most reliable objective motion forecast aids employed at JTWC.

In contrast to predicting persistent tropical cyclone motion was the ability to forecast direction changes. Back propagation, correlation analysis and JTWC correctly forecast non-persistent motion events roughly 40 percent of the time (Figure 11 and Appendix A), whereas, OTCM predicted 67 percent of the non-persistent motion. Neither pattern recognition techniques could predict non-persistent motion of tropical cyclones traveling with a northward component (Figure 12). JTWC and the three objective aids forecast better in this respect than back propagation and correlation analysis. Both pattern recognition techniques predicted non-persistent motion quite well for tropical cyclones tracking southwestward.

In summary, back propagation and correlation analysis were biased toward issuing northwest forecasts whenever the tropical cyclone was tracking southwestward, resulting in an overall performance above persistence. However, the high forecast accuracy of persistent motion and low forecast ability of non-persistent scenarios indicate both techniques were biased toward forecasting persistence for northward moving tropical cyclones.

5.2 Forecasting Short-Term Intensification

Correlation analysis was a poor technique for predicting short-term intensification (Figure 13 and Appendix D). Although JTWC verified better at +/- 0 T-number difference, back propagation and JTWC verified at a similar rate with +/- 0.5 T-number difference. Back propagation verified better than JTWC at +/- 1 T-number and greater. Back propagation predicted intensification better than the "no-skill" modal distributions based upon past motion, past intensity change and current intensity (Figure 14).

5.3 Influence of the Number of Variables and Levels on Forecasting Short-Term Quadrant of Motion

Adding combinations of levels and variables did not improve the ability of back propagation and correlation analysis to predict short-term quadrant of motion (Appendix E). Results of both techniques using increased information produced forecasts similar to those obtained using one variable at one level.

The back propagation technique improved when a single variable at one level was combined with the forecasts made by JTWC, OTCM and HPAC (CSUM was omitted due to a low number of forecasts made during 1978 through 1987, the time period of the training database.) (Appendix F). The accuracy was not better than HPAC's overall forecast ability nor was it better than OTCM's ability to forecast non-persistent events. However, the results blended the best characteristics of OTCM (the ability to predict non-persistent events) and HPAC (low rates of false start forecasts).

5.4 Influence of Training Set

The training data set used to train neural networks has a significant effect on the performance of the neural network, for example, local minima[13] and the rigidity of back propagation (stability-plasticity dilemma, Carpenter and Grossberg[14]). It is frequently stated that

13. Simpson, P.K. (1990): Artificial Neural Systems: Foundations, Paradigms, Applications and Implementations, Pergamon Press, 209 pp.

14. Carpenter, G. and S. Grossberg (1986) Neural Dynamics of Category Learning and Recognition: Attention, Memory Consolidation and Amnesia. In Brain Structure, Learning and Memory (AAAS Symposium Series), eds. J. Davis, R. Newburgh and E. Wegman.

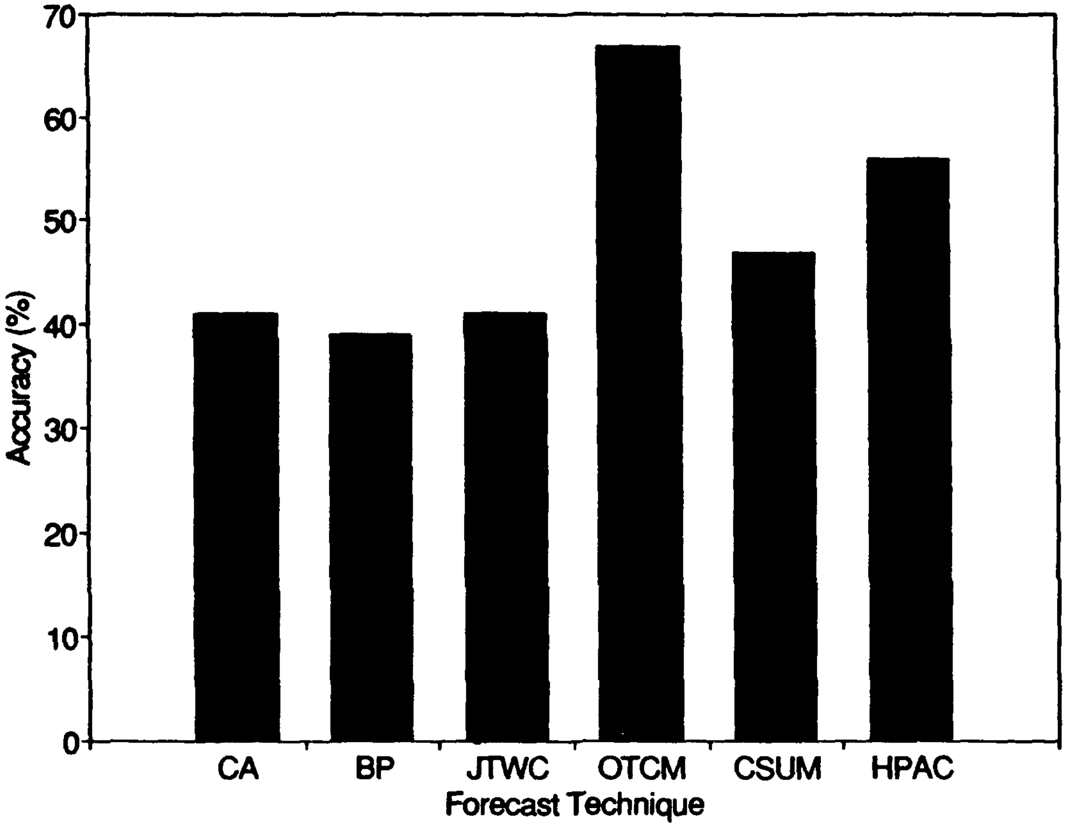

Figure 11 Forecast accuracy of the quadrant of motion for non-persistent motion events. CA and BP represent results using correlation analysis and back propagation techniques, respectively. JTWC represents forecasts issued by the Joint Typhoon Warning Center (JTWC), Guam; and OTCM, CSUM and HPAC are the results of the three most reliable objective motion forecast aids employed at JTWC.

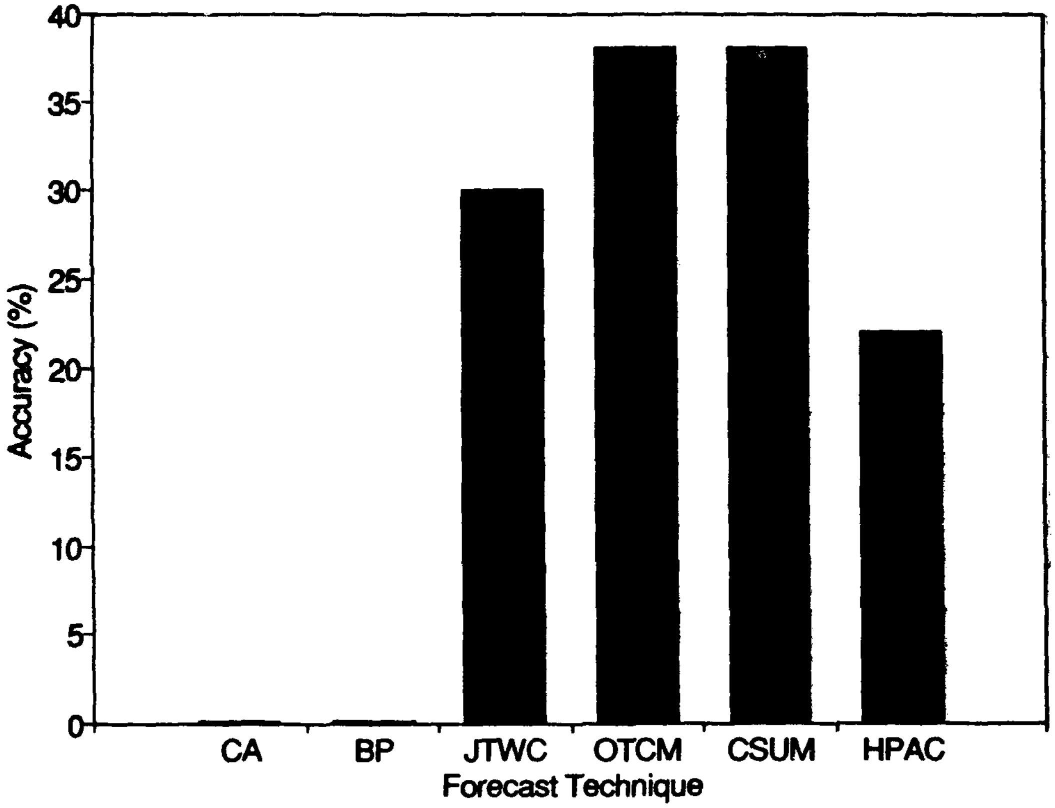

Figure 12 Forecast accuracy of the quadrant of motion for non-persistent northward motion events. CA and BP represent results using correlation analysis and back propagation techniques, respectively. JTWC represents forecasts issued by the Joint Typhoon Warning Center (JTWC), Guam; and OTCM, CSUM and HPAC are the results of the three most reliable objective motion forecast aids employed at JTWC.

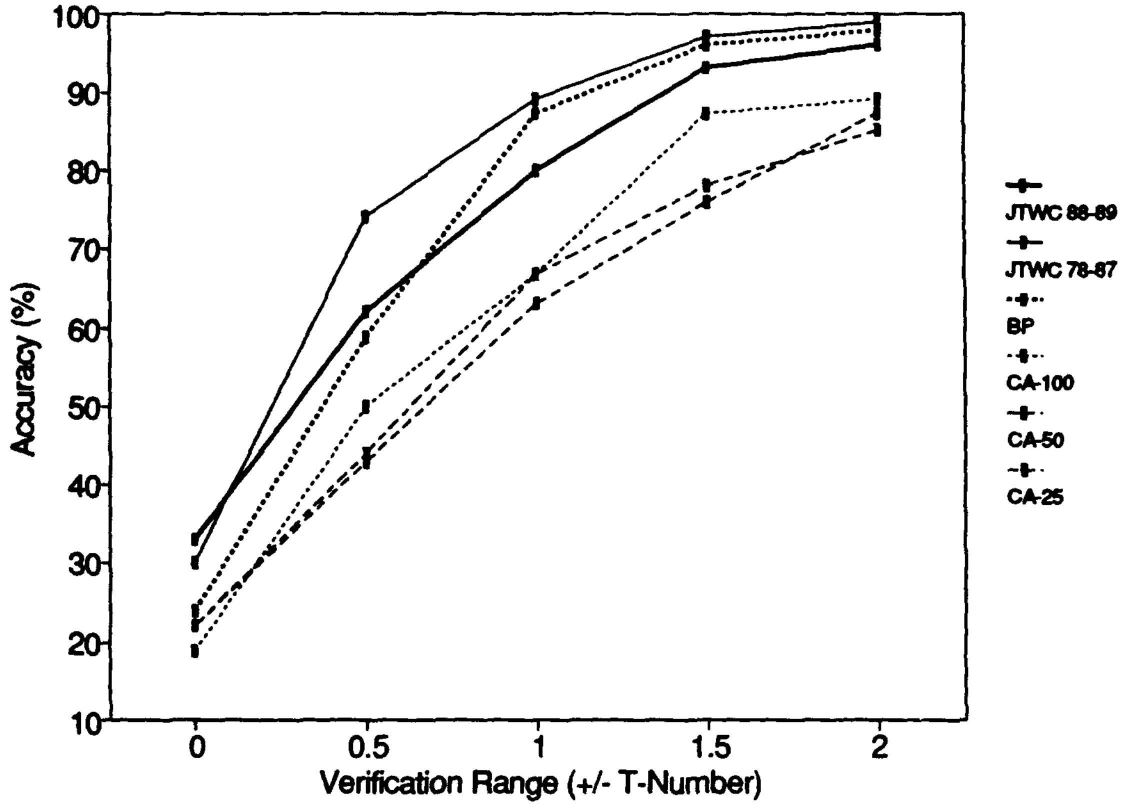

Figure 13 Forecast accuracy of intensification for the forecasters at JTWC (1988 to 1989 and 1978 to 1987), back propagation (BP) and correlation analysis (CA). The three results for CA are based on the three intensity ranges used to screen fields for the correlation calculation. For example, CA-100 indicates that only cases form the developmental database with a current intensity within 100 knots of the current intensity of the test case were used in the correlation analysis technique.

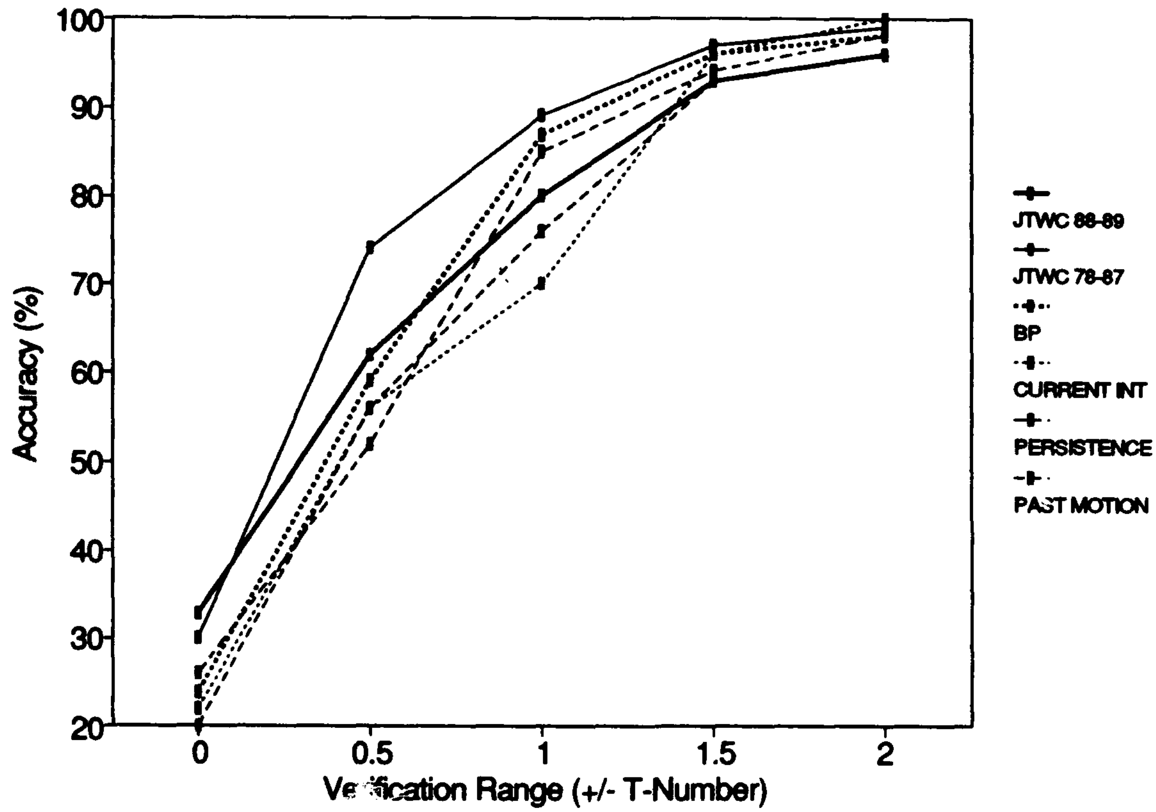

Figure 14 Forecast accuracy of intensification for the forecasters at JTWC (1988 to 1989 and 1978 to 1987), back propagation (BP), and three "no-skill" forecast techniques that are based on either persistence or the modal distribution of climatology (see Table 3). Persistence is based on forecasting the past intensification into the future. Past Motion represents the forecasts based on the modal locations observed within the 1978 to 1987 distribution of past quadrant of motion and future intensification. Current Int represents forecasts based on the modal locations observed within the 1978 to 1987 distribution of current intensity and future intensification.

with optimum training sets, neural networks are capable of performing at outstanding levels. Unfortunately, with meteorology and synoptic fields, determining and acquiring optimum training sets is very difficult.

In one test of the influence of the training set in forecasting tropical cyclone movement (quadrant of motion), the distribution of persistent versus non-persistent events was varied within the training set (Figure 15 and Appendix G). The back propagation networks were trained with 375 input nodes per case (25 grid points of the 5 x 5 field for 3 variables at 5 levels). When the entire 10-year database was used (292 cases), overall forecast accuracy was 74 percent with a false start rate of 5 percent and a non-persistent forecast ability of 29 percent. When the training set was reduced to 214 cases by including only two-thirds (randomly selected) of the persistent cases, forecast accuracy decreased to 59 percent, the false start rate rose to 35 percent and the ability to forecast non-persistent events increased to 42 percent. When the training set was reduced to 176 cases (only one half of the persistent cases were included), overall performance continued to decrease and the rate of false starts and the ability to forecast non-persistent events increased.

Three additional tests examined the influence of the training set data on the performance of the back propagation technique. First, the past 12-hour quadrant of motion was incorporated into the training set data instead of training four distinct networks based on past motion. The result was a significant degradation of the performance (Appendix H, Section A). There was no improvement with the addition of current intensity of the tropical cyclone in the training set (Appendix H, Section B). And finally, the exclusion of the central grid point (representing the tropical cyclone) from the training set fields did not have an effect (Appendix H, Section C).

6. CONCLUSIONS

Preliminary results suggest that back propagation and correlation analysis pattern recognition techniques are able to forecast the short-term movement and intensification of tropical cyclones at least as well as persistence. With respect to intensification, back propagation performed better than the forecasters at JTWC, persistence and climatology. These results are encouraging due to the coarse observation grid and in light of the simplicity of the techniques evaluated in this study. The data, which included the height and u and v components of the wind at five upper-air levels, were sparsely distributed throughout the western North Pacific region. These data were objectively analyzed onto a grid. Neither satellite data nor aircraft reports were used to fill in the data voids, nor were physics included in the study to add greater complexity to the fields. The back propagation technique was quite basic; there were no individual neural modules manipulating the training data, for example, determining the shapes and orientations of contours. In fact, neither pattern recognition technique utilized contours and the associated information. The techniques used only a sequential series of numbers that represent a two-dimensional field distribution on a 5 x 5 grid, that is, a series of 25 numbers in order to determine a pattern.

The back propagation and correlation analysis techniques required fine-tuning to improve the forecasting ability to the levels presented in this report. Using the techniques "straight from the

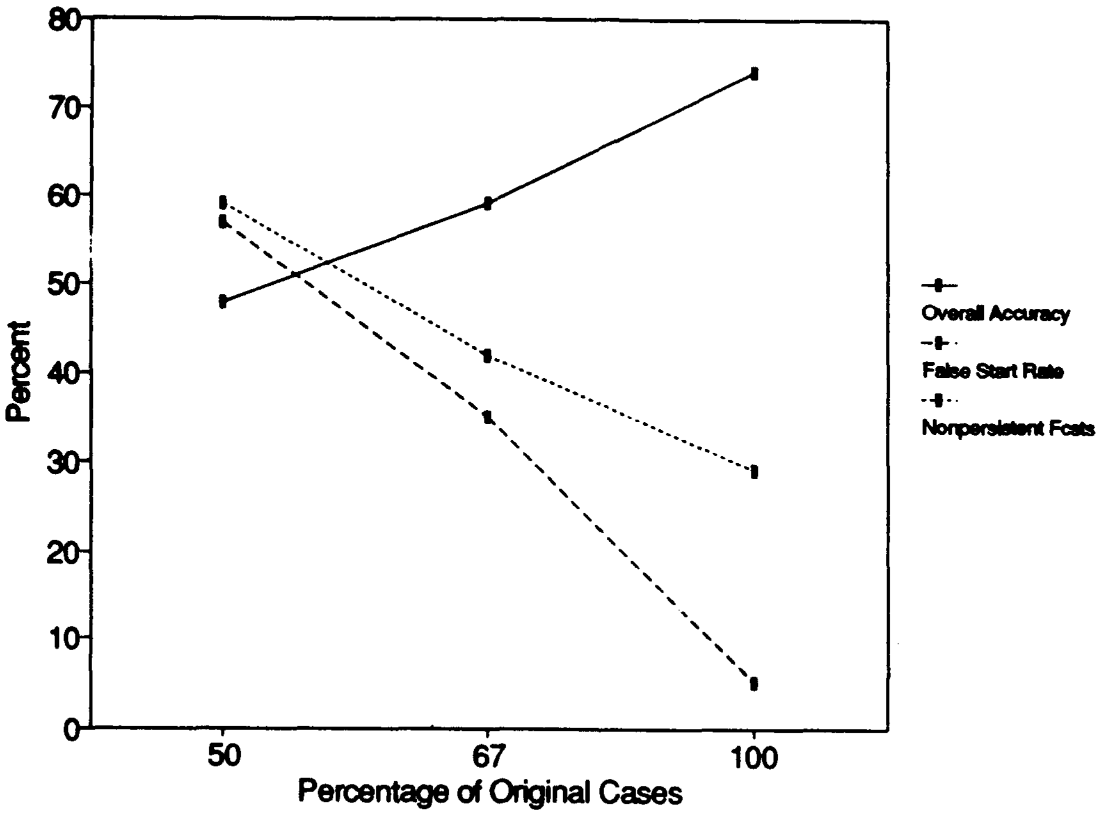

Figure 15 The effect of the training set data on the ability of back propagation to forecast the quadrant of motion. The ratio of persistent to non-persistent motion events was changed. Persistent cases were randomly eliminated. Overall accuracy is the percent of accurate forecasts, nonpersistent fcsts represents the accuracy of forecasting nonpersistent motion events, and false start rate is the percentage of nonpersistent forecasts for persistent motion events.

box" produced results that were considerably worse than persistence. Insights into the problems and techniques of forecasting tropical cyclone movement and techniques of forecasting tropical cyclone movement and intensification were necessary to improve the performance of the two techniques. Correlation analysis required the separation of data fields into four quadrants; the orientation of which were not critical. Dividing the fields into quadrants did not improve the results for back propagation. Both back propagation and correlation analysis required information about the motion of the tropical cyclone during the past 12 hours. Simply adding the quadrant of motion to the data was not useful. Based on the quadrant of motion, four separate networks were trained using back propagation. Correlation analysis compared only cases with similar past motion. This special consideration of the past quadrant of motion suggests that patterns in the surrounding fields may not be consistently or significantly associated with specific tropical cyclone movement.

With respect to forecasting short-term quadrant of motion, neither back propagation nor correlation analysis could outperform persistence for tropical cyclones that were already travelling with a northward component. Therefore, both techniques issued nonpersistent forcasts as well as persistent ones based on field patterns. This suggests that relatively similar patterns within these data fields are associated with both persistent and nonpersistent events.

No single level or variable provided optimal insight into both movement and intensification. Patterns within each of the upper-air levels and variables could be used to forecast either the quadrant of motion or intensification. Interestingly, neither technique improved when the number of variables and levels increased. Either the additional field data did not provide significantly different information from the first field, or there is a limit to the utility of pattern information in forecasting movement and intensification. The lack of significant difference between patterns associated with specific tropical cyclone movement is supported by the test that changed the ratio of persistent to non-persistent cases in the training data set. As the ratio of persistent to non-persistent cases decreased, both the ability to forecast non-persistent motion and the rate of false start forecasts increased. This suggests that many of the patterns classified by back propagation were associated with both persistent and non -persistent motion. The ratio of these motions determined the forecast of the neural network.

The ability to forecast the short-term quadrant of motion using the back propagation technique was improved considerably by including the forecasts issued by JTWC, OTCM and GPAC to the input data. The results were not better than any of the individual objective techniques, but the strengths of OTCM (good ability to forecast non-persistent events) and HPAC (low false start rate) were utilized.

JTWC forecast short-term intensification best before 1987. One possible reason for the subsequent reduction of JTWC's ability to forecast intensity is that aircraft reconnaissance was stopped after August, 1987. Forecasters at JTWC no longer had verification of intensities derived by satellite at the time of the forecast. Ground truthing of the current intensity helps determine the past change in intensity with more confidence at the time of the forecast, thereby helping the

Dvorak method make a better forecast. In addition, forecasters no longer had potential temperature data for use with Dunnavan's [15] technique for forecasting explosive deepening.

The influence of the best tracking techniques at JTWC needs to be reassessed. Best tracking techniques create the finalized coordinates of tropical cyclone position and intensity as best determined from all the available data received at JTWC. These techniques emphasize that the final track (best track) has as smooth direction and speed changes in track and intensification as possible. For example, the Dvorak technique, used to determine the tropical cyclone intensity, strongly encourages changes in intensity to be limited to +/- 2 T-numbers. These best tracking techniques can eliminate subtle signals within the response of the tropical cyclone that may be useful for future objective forecast aids of movement and intensification. This study should be evaluated using tropical cyclone tracks and intensities determined by an objective best tracking technique that does not emphasize gradual tropical cyclone behavior.

Once trained, back propagation issues forecasts very quickly and does not require large storage space within the computer. On the other hand, correlation analysis takes a considerably long time to issue a forecast and requires a large storage space within the computer. Since the results of forecasting short-term movement by back propagation were roughly equivalent to correlation analysis and were considerably better for predicting intensification, future efforts should be focused on back propagation or possibly other more advanced neural networks. Forecasting intensification should be emphasized because JTWC needs objective techniques in this area.

Additional data should be incorporated into the input data improve the detail that can be recognized by back propagation, possibly eliminating the observed overlap of tropical cyclone responses for recognized patterns within the coarse height and wind fields. In particular, adding satellite imagery would be ideal because the data is densely distributed about the tropical cyclone and would require minimal preparation, such as objectively analyzing the imagery first. Moreover, neural network modules that recognize textures, boundaries, and shapes of imagery, would increase the types of information gleaned from satellite imagery, thereby increasing the likelihood of recognizing subtle patterns that are associated with specific tropical cyclone behavior.

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15. Dunnavan, G. M. (1981): Forecasting Intense Tropical Cyclones Using 700mb Equivalent Potential Temperature and Central Sea-Level Pressure. NAVOCEANOCOMCEN/JTWC TECH NOTE 81-1,12 pp.

Appendix A

Accuracy of short-term quadrant of motion forecasts from 1988 to 1989.

Persistence represents the accuracy of persistent forecasts. Two pattern schemes were used to divide data fields in correlation analysis (Figure 2).

FORECAST TYPE	OVERALL ABILITY	FALSE STARTS	NON-PERSISTENT FORECASTS	PERSISTENCE	PATTERN
JTWC	76	8	41	69	
OTCM	77	17	67	66	
CSUM	76	10	47	67	
HPAC	83	3	56	67	
JTWC*	75	12	34	76	
OTCM*	77	15	44	78	
CSUM*	79	11	52	72	
HPAC*	75	14	40	77	
BP-P7	56	35	39	67	
BP-P5	75	8	39	67	
BP-P4	75	14	39	67	
BP-P3	76	5	39	67	
BP-P2	76	5	39	67	
BP-U7	65	19	33	67	
BP-U5	75	5	33	67	
BP-U4	71	8	28	67	
BP-U3	76	5	35	67	
BP-U2	76	5	35	67	
BP-V7	75	3	28	67	
BP-V5	65	11	17	67	
BP-V4	69	8	22	67	
BP-V3	76	3	29	67	
BP-V2	78	0	29	67	
CA-P7	67	8	17	67	1
CA-P5	71	8	28	67	1
CA-P4	76	3	33	67	1
CA-P3	71	11	33	67	1
CA-P2	71	11	33	67	1
CA-U7	69	11	28	67	1
CA-U5	75	8	39	67	1
CA-U4	76	5	39	67	1
CA-U3	76	5	35	67	1
CA-U2	76	8	41	67	1
CA-V7	69	8	22	67	1
CA-V5	62	14	11	67	1
CA-V4	71	5	22	67	1
CA-V3	74	5	29	67	1
CA-V2	74	5	29	67	1

* Performance during 1978 to 1987.

Appendix A Continued.

FORECAST TYPE	OVERALL ABILITY	FALSE STARTS	NON-PERSISTENT FORECASTS	PERSISTENCE	PATTERN
CA-P7	65	11	17	67	2
CA-P5	75	5	33	67	2
CA-P4	71	5	22	67	2
CA-P3	73	8	33	67	2
CA-P2	71	8	28	67	2
CA-U7	71	8	28	67	2
CA-U5	71	8	20	67	2
CA-U4	75	8	39	67	2
CA-U3	76	5	41	67	2
CA-U2	74	11	41	67	2
CA-V7	69	11	28	67	2
CA-V5	64	11	17	67	2
CA-V4	65	11	28	67	2
CA-V3	72	5	24	67	2
CA-V2	72	5	24	67	2

KEY TO FORECAST TYPE

JTWC : results of forecasts issued by the Joint Typhoon Warning Center, Guam
OTCM : results of forecasts issued by the objective dynamic aid, the One-Way Tropical Cyclone Model
CSUM : results of forecasts issued by the objective statistical aid, the Colorado State University Model
HPAC : results of forecasts issued by the objective aid, Half Persistence and Climatology Model
BP- : results of forecasts issued by the pattern recognition technique, Back Propagation
CA- : results of forecasts issued by the pattern recognition technique, Correlation Analysis

FIELDS USED BY PATTERN RECOGNITION TECHNIQUES

-P# : geopotential height at #00 mb
-U# : u-component of the wind at #00 mb
-V# : v-component of the wind at #00 mb

Appendix B

Accuracy of short-term quadrant of motion forecasts of persistent motion events with respect to the observed past motion (-12) hr) of the tropical cyclone from 1988 to 1989.

Persistence represents the percentage of persistent motion events.

FORECAST TYPE	FORECAST NE	FORECAST SW	FORECAST NW	FORECAST NE & NW	PERSISTENCE NE	PERSISTENCE SW	PERSISTENCE NW	PERSISTENCE NE & NW
JTWC	100	56	72	80	93	22	72	78
OTCM	56	100	79	73	89	0	75	78
CSUM	80	57	79	79	90	0	75	79
HPAC	92	100	76	80	92	0	72	78
JTWC*	79	50	78	78	86	22	79	78
OTCM*	69	40	85	80	85	20	81	82
CSUM*	88	100	76	79	76	0	76	76
HPAC*	65	61	82	77	87	22	79	81
BP-P7	69	56	52	57	92	22	70	76
BP-P5	92	67	70	76	92	22	70	76
BP-P4	92	78	61	70	92	22	70	76
BP-P3	92	78	70	76	92	22	70	76
BP-P2	92	78	70	76	92	22	70	76
BP-U7	54	56	73	67	92	22	70	76
BP-U5	92	67	70	76	92	22	70	76
BP-U4	85	56	70	74	92	22	70	76
BP-U3	92	67	70	76	92	22	70	76
BP-U2	92	67	70	76	92	22	70	76
BP-V7	92	56	70	76	92	22	70	76
BP-V5	76	33	70	72	92	22	70	76
BP-V4	85	44	70	76	92	22	70	76
BP-V3	92	67	70	76	92	22	70	76
BP-V2	92	78	70	76	92	22	70	76
Pattern 1								
CA-P7	85	33	70	74	92	22	70	76
CA-P5	85	56	70	74	92	22	70	76
CA-P4	92	78	70	76	92	22	70	76
CA-P3	77	67	70	72	92	22	70	76
CA-P2	77	67	70	72	92	22	70	76
CA-U7	77	56	70	72	92	22	70	76
CA-U5	85	78	70	74	92	22	70	76
CA-U4	92	78	70	76	92	22	70	76
CA-U3	92	67	70	76	92	22	70	76
CA-U2	92	78	70	76	92	22	70	76
CA-V7	92	44	67	74	92	22	70	76
CA-V5	92	22	61	70	92	22	70	76
CA-V4	92	44	70	76	92	22	70	76
CA-V3	92	56	70	76	92	22	70	76
CA-V2	85	67	70	74	92	22	70	76

* Performance during 1978 to 1987.

Appendix B Continued.

FORECAST TYPE	FORECAST NE	SW	NW	NE & NW	PERSISTENCE NE	SW	NW	NE & NW
Pattern 2								
CA-P7	77	33	70	72	92	22	70	76
CA-P5	92	67	70	76	92	22	70	76
CA-P4	92	44	70	76	92	22	70	76
CA-P3	85	67	70	74	92	22	70	76
CA-P2	85	67	67	72	92	22	70	76
CA-U7	77	67	70	72	92	22	70	76
CA-U5	85	56	70	74	92	22	70	76
CA-U4	92	78	67	74	92	22	70	76
CA-U3	92	67	70	76	92	22	70	76
CA-U2	92	78	64	72	92	22	70	76
CA-V7	92	56	64	72	92	22	70	76
CA-V5	92	22	64	72	92	22	70	76
CA-V4	77	44	67	70	92	22	70	76
CA-V3	92	44	70	76	92	22	70	76
CA-V2	92	56	67	74	92	22	70	76

KEY TO FORECAST TYPE

JTWC : results of forecasts issued by the Joint Typhoon Warning Center, Guam
OTCM : results of forecasts issued by the objective dynamic aid, the One-Way Tropical Cyclone Model
CSUM : results of forecasts issued by the objective statistical aid, the Colorado State University Model
HPAC : results of forecasts issued by the objective aid, Half Persistence and Climatology Model
BP- : results of forecasts issued by the pattern recognition technique, Back Propagation
CA- : results of forecasts issued by the pattern recognition technique, Correlation Analysis

FIELDS USED BY PATTERN RECOGNITION TECHNIQUES

-P# : geopotential height at #00 mb
-U# : u-component of the wind at #00 mb
-V# : v-component of the wind at #00 mb

Appendix C

Accuracy of forecasts for persistent scenarios and non-persistent forecasts excluding cases with a past southwestward motion (-12 hr).

In the cast of JTWC and the three objective aids, forecasts were not always made for each of the test cases forecast by back propagation (BP) and correlation analysis (CA).

FORECAST	PERSISTENT SCENARIOS				NON-PERSISTENT
TYPE	NE	SW	NW	TOTAL	SCENARIOS
JTWC	100	50	91	92	30
OTCM	50	-	95	83	38
CSUM	89	-	90	90	38
HPAC	91	-	100	97	22
JTWC*	87	25	91	88	30
OTCM*	69	0	93	86	17
CSUM*	100	-	88	89	41
HPAC*	67	0	97	86	30
BP-P7	67	0	70	65	18
BP-P5	92	0	100	92	9
BP-P4	100	0	87	87	0
BP-P3	100	0	100	95	0
BP-P2	100	0	100	95	0
BP-U7	58	0	100	81	0
BP-U5	100	0	100	95	0
BP-U4	92	0	100	92	0
BP-U3	100	0	100	95	0
BP-U2	100	0	100	95	0
BP-V7	100	0	100	95	0
BP-V5	83	0	100	89	0
BP-V4	92	0	100	92	0
BP-V3	100	50	100	97	0
BP-V2	100	100	100	100	0
<u>Pattern 1</u>					
CA-P7	92	0	100	92	0
CA-P5	92	0	100	92	0
CA-P4	100	50	100	97	0
CA-P3	83	0	100	89	0
CA-P2	83	0	100	89	0
CA-U7	83	0	100	89	0
CA-U5	92	0	100	92	0
CA-U4	100	0	100	97	0
CA-U3	100	0	100	92	0
CA-U2	100	0	96	92	0
CA-V7	100	0	96	92	0
CA-V5	100	0	87	86	0
CA-V4	100	0	100	97	0
CA-V3	100	0	100	97	0
CA-V2	92	50	100	97	0

* Performance during 1978 to 1987.

Appendix C Continued.

FORECAST TYPE	PERSISTENT SCENARIOS NE	SW	NW	TOTAL	NON-PERSISTENT SCENARIOS
Pattern 2					
CA-P7	83	0	100	89	0
CA-P5	100	0	100	95	0
CA-P4	100	0	100	95	0
CA-P3	92	0	100	92	0
CA-P2	92	50	96	89	0
CA-U7	83	50	100	92	0
CA-U5	92	0	100	92	0
CA-U4	100	0	96	92	0
CA-U3	100	0	100	95	0
CA-U2	100	0	91	89	0
CA-V7	100	0	91	89	0
CA-V5	100	0	91	89	0
CA-V4	83	50	96	89	0
CA-V3	100	0	100	95	0
CA-V2	100	50	96	95	0

KEY TO FORECAST TYPE

JTWC : results of forecasts issued by the Joint Typhoon Warning Center, Guam
OTCM : results of forecasts issued by the objective dynamic aid, the One-Way Tropical Cyclone Model
CSUM : results of forecasts issued by the objective statistical aid, the Colorado State University Model
HPAC : results of forecasts issued by the objective aid, Half Persistence and Climatology Model
BP- : results of forecasts issued by the pattern recognition technique, Back Propagation
CA- : results of forecasts issued by the pattern recognition technique, Correlation Analysis

FIELDS USED BY PATTERN RECOGNITION TECHNIQUES

-P# : geopotential height at #00 mb
-U# : u-component of the wind at #00 mb
-V# : v-component of the wind at #00 mb

Appendix D

Accuracy of short-term intensification forecasts from 1988 to 1989 verified within specified T-number ranges.

Data used by back propagation (BP) included current intensity of the tropical cyclone. Correlation analysis (CA) used two pattern schemes (Figure 2) with three ranges in current intensity (CI) used to select cases from the developmental database cases to be included in the correlation calculation.

FCST	T-NUMBER RANGE					PATTERN	CI
TYPE	0.0	0.5	1.0	1.5	2.0	SCHEME	+/-
JTWC	33	62	80	93	96		
JTWC*	30	74	89	97	99		
BP-P7	17	60	78	93	98		
BP-P5	17	52	70	89	96		
BP-P4	22	57	80	94	96		
BP-P3	22	61	80	98	100		
BP-P2	17	50	76	94	98		
BP-U7	24	57	76	96	100		
BP-U5	17	41	61	74	87		
BP-U4	20	52	70	80	94		
BP-U3	24	59	87	96	98		
BP-U2	22	59	83	93	98		
BP-V7	24	57	74	85	94		
BP-V5	17	57	72	89	98		
BP-V4	20	56	70	81	94		
BP-V3	22	57	76	93	98		
BP-V2	17	43	65	80	89		
CA-P7	13	43	48	65	69	1	100
CA-P5	17	41	54	74	83	1	100
CA-P4	15	33	48	67	72	1	100
CA-P3	11	35	48	65	72	1	100
CA-P2	7	39	48	63	70	1	100
CA-U7	9	30	46	67	72	1	100
CA-U5	7	31	54	69	81	1	100
CA-U4	9	35	52	69	81	1	100
CA-U3	17	41	56	67	81	1	100
CA-U2	17	43	65	74	81	1	100
CA-V7	11	33	52	69	72	1	100
CA-V5	11	30	46	59	70	1	100
CA-V4	7	28	41	57	67	1	100
CA-V3	13	33	52	65	74	1	100
CA-V2	19	39	46	61	69	1	100

* Performance during 1978 to 1987.

Appendix D Continued.

FCST TYPE	T-NUMBER RANGE 0.0	0.5	1.0	1.5	2.0	PATTERN SCHEME	CI +/-
CA-P7	9	39	52	67	70	1	50
CA-P5	22	44	67	78	85	1	50
CA-P4	24	43	59	65	74	1	50
CA-P3	6	33	48	61	65	1	50
CA-P2	11	35	56	70	72	1	50
CA-U7	9	30	46	67	72	1	50
CA-U5	13	44	56	69	72	1	50
CA-U4	9	33	50	59	70	1	50
CA-U3	20	46	65	72	80	1	50
CA-U2	13	43	61	76	80	1	50
CA-V7	15	44	63	70	78	1	50
CA-V5	13	35	48	59	70	1	50
CA-V4	4	28	44	56	63	1	50
CA-V3	13	30	48	50	57	1	50
CA-V2	24	43	54	67	72	1	50
CA-P7	11	43	56	80	81	1	25
CA-P5	22	43	63	76	87	1	25
CA-P4	19	37	57	65	76	1	25
CA-P3	13	43	56	70	78	1	25
CA-P2	7	35	44	61	69	1	25
CA-U7	17	35	52	69	76	1	25
CA-U5	6	39	56	76	87	1	25
CA-U4	9	33	48	61	72	1	25
CA-U3	19	41	57	69	83	1	25
CA-U2	17	41	59	74	83	1	25
CA-V7	15	41	56	65	70	1	25
CA-V5	11	37	52	57	65	1	25
CA-V4	4	31	57	67	74	1	25
CA-V3	11	28	48	56	65	1	25
CA-V2	22	43	52	67	74	1	25
CA-P7	15	48	56	67	72	2	100
CA-P5	19	50	67	87	89	2	100
CA-P4	11	37	56	76	85	2	100
CA-P3	22	43	54	70	81	2	100
CA-P2	15	46	59	76	85	2	100
CA-U7	6	33	48	67	76	2	100
CA-U5	7	31	46	59	78	2	100
CA-U4	7	19	33	50	67	2	100
CA-U3	17	43	61	74	83	2	100
CA-U2	20	44	63	76	83	2	100
CA-V7	9	33	48	57	65	2	100
CA-V5	11	30	54	63	74	2	100
CA-V4	6	35	50	59	70	2	100
CA-V3	13	39	54	61	70	2	100
CA-V2	13	33	50	61	69	2	100

FCST TYPE	T-NUMBER 0.0	0.5	1.0	1.5	2.0	PATTERN SCHEME	CI +/-
CA-P7	17	43	57	69	72	2	50
CA-P5	19	37	57	72	76	2	50
CA-P4	19	39	54	67	74	2	50
CA-P3	17	48	59	72	78	2	50
CA-P2	7	37	52	65	69	2	50
CA-U7	9	31	41	52	61	2	50
CA-U5	11	39	43	52	63	2	50
CA-U4	17	37	54	63	72	2	50
CA-U3	11	35	61	74	78	2	50
CA-U2	19	41	59	69	74	2	50
CA-V7	13	44	57	70	72	2	50
CA-V5	11	35	43	54	61	2	50
CA-V4	7	30	46	54	63	2	50
CA-V3	11	35	48	56	59	2	50
CA-V2	17	39	56	65	70	2	50
CA-P7	15	44	56	70	76	2	25
CA-P5	13	35	59	78	81	2	25
CA-P4	20	39	56	70	78	2	25
CA-P3	17	43	50	61	76	2	25
CA-P2	11	44	59	72	80	2	25
CA-U7	11	35	46	61	69	2	25
CA-U5	17	41	48	57	69	2	25
CA-U4	13	31	44	59	74	2	25
CA-U3	19	41	63	78	83	2	25
CA-U2	19	46	63	76	85	2	25
CA-V7	13	41	57	69	70	2	25
CA-V5	7	30	43	56	65	2	25
CA-V4	6	39	54	56	67	2	25
CA-V3	13	41	56	63	69	2	25
CA-V2	13	31	43	52	52	2	25

KEY TO FORECAST TYPE

JTWC : results of forecasts issued by the Joint Typhoon Warning Center, Guam
OTCM : results of forecasts issued by the objective dynamic aid, the One-Way Tropical Cyclone Model
CSUM : results of forecasts issued by the objective statistical aid, the Colorado State University Model
HPAC : results of forecasts issued by the objective aid, Half Persistence and Climatology Model
BP- : results of forecasts issued by the pattern recognition technique, Back Propagation
CA- : results of forecasts issued by the pattern recognition technique, Correlation Analysis

FIELDS USED BY PATTERN RECOGNITION TECHNIQUES

-P# : geopotential height at #00 mb
-U# : u-component of the wind at #00 mb
-V# : v-component of the wind at #00 mb

Appendix E

Accuracy of short-term quadrant of motion of forecasts from 1988 to 1989.

Back propagation (BP) and correlation analysis (CA) identified patterns within combined fields of geopotential height and u and v components of the wind at various pressure levels. ALL represents forecasts based on the height and wind fields at all five levels. Two pattern schemes were used to divide the data fields using correlation analysis (Figure 2). Persistence represents the accuracy of persistent forecasts.

FORECAST TYPE	OVERALL ABILITY	FALSE STARTS	NON-PERSISTENT FORECASTS	PERSISTENCE	PATTERN
BP-UV7	76	8	41	67	
BP-UV5	78	5	41	67	
BP-UV4	78	5	41	67	
BP-UV3	78	5	41	67	
BP-UV2	78	0	29	67	
BP-PUV7	78	5	41	67	
BP-PUV5	78	5	41	67	
BP-PUV4	74	3	24	67	
BP-PUV3	74	5	29	67	
BP-PUV2	78	5	41	67	
BP-ALL	74	5	29	67	
CA-UV7	70	8	24	67	1
CA-UV5	69	8	18	67	1
CA-UV4	76	5	35	67	1
CA-UV3	70	8	24	67	1
CA-PUV7	74	5	29	67	1
CA-PUV5	74	5	29	67	1
CA-PUV4	78	5	41	67	1
CA-PUV3	78	5	41	67	1
CA-PUV2	76	5	35	67	1
CA-ALL	78	3	35	67	1
CA-UV2	76	5	35	67	1
CA-UV7	76	5	35	67	2
CA-UV5	69	8	18	67	2
CA-UV4	76	3	29	67	2
CA-UV3	74	5	29	67	2
CA-UV2	69	14	29	67	2
CA-PUV7	76	3	29	67	2
CA-PUV5	74	5	29	67	2
CA-PUV4	78	5	41	67	2
CA-PUV3	74	5	29	67	2
CA-PUV2	74	8	35	67	2
CA-ALL	76	5	35	67	2

KEY TO FORECAST TYPE

BP- : results of forecasts issued by the pattern recognition technique, Back Propagation
CA- : results of forecasts issued by the pattern recognition technique, Correlation Analysis

FIELDS USED BY PATTERN RECOGNITION TECHNIQUES

-P# : geopotential height at #00 mb
-U# : u-component of the wind at #00 mb
-V# : v-component of the wind at #00 mb

Appendix F

Accuracy of short-term quadrant of motion forecasts from 1988 to 1989.

Training sets for the back propagation neural network contained corresponding forecasts of JTWC, OTCM and HPAC. Persistence represents the accuracy of persistent forecasts for corresponding data sets.

FORECAST TYPE	OVERALL ABILITY	FALSE STARTS	NON-PERSISTENT FORECASTS	PERSISTENCE
BP-P7	67	18	40	65
BP-P5	65	25	47	65
BP-P4	65	18	33	65
BP-P3	79	0	40	65
BP-P2	79	3	47	65
BP-U7	74	14	53	65
BP-U5	74	7	47	65
BP-U4	74	14	53	65
BP-U3	81	4	53	65
BP-U2	81	11	67	65
BP-V7	79	4	47	65
BP-V5	72	4	27	55
BP-V4	70	7	27	65
BP-V3	79	7	53	65
BP-V2	65	4	7	65

KEY TO FORECAST TYPE

BP- : results of forecasts issued by the pattern recognition technique, Back Propagation
CA- : results of forecasts issued by the pattern recognition technique, Correlation Analysis

FIELDS USED BY PATTERN RECOGNITION TECHNIQUES

-P# : geopotential height at #00 mb
-U# : u-component of the wind at #00 mb
-V# : v-component of the wind at #00 mb

Appendix G

Accuracy of short-term quadrant of motion forecasts from 1988 to 1989.

Back propagation (BP) networks were trained using the geopotential height and wind fields at all five pressure levels, but with varying percentages of persistent to non-persistent cases.

PERCENT ORIGINAL PERSISTENT CASES	NUMBER OF CASES IN TRAINING SET	OVERALL ABILITY	FALSE STARTS	NON-PERSISTENT FORECASTS
100	292	74	5	29
67	214	59	35	42
50	176	48	57	59

Appendix H

Accuracy of short-term quadrant of motion forecasts from 1988 to 1989 made by back propagation (BP).

Training sets were modified in order to test the neural network's response. Persistence represents the accuracy of persistent forecasts.

a. Past movement included into the training set data rather than train four distinct networks based on past movement.

FORECAST TYPE	OVERALL ABILITY	FALSE STARTS	NON-PERSISTENT FORECASTS	PERSISTENCE
BP-P7	59	35	47	67
BP-P5	65	27	47	67
BP-P4	17	22	18	67
BP-P3	57	38	47	67
BP-P2	57	38	47	67
BP-U7	57	38	47	67
BP-U5	57	38	47	67
BP-U4	54	43	47	67
BP-U3	57	38	47	67
BP-U2	57	38	47	67
BP-V7	50	46	41	67
BP-V5	56	43	53	67
BP-V4	52	49	53	67
BP-V3	61	41	65	67
BP-V2	48	46	35	67

b. Current intensity (maximum sustained winds at the time of the forecast) was included into the training set data. Four distinct networks were trained based on the quadrant of past movement.

FORECAST TYPE	OVERALL ABILITY	FALSE STARTS	NON-PERSISTENT FORECASTS	PERSISTENCE
BP-P7	60	30	39	67
BP-P5	69	11	28	67
BP-P4	75	11	44	67
BP-P3	75	11	44	67
BP-P2	76	8	44	67
BP-U7	71	16	44	67
BP-U5	75	5	33	67
BP-U4	71	5	22	67
BP-U3	72	5	24	67
BP-U2	78	3	35	67
BP-V7	65	19	33	67
BP-V5	67	8	18	67
BP-V4	71	8	29	67
BP-V3	76	3	29	67
BP-V2	76	0	24	67

Appendix H Continued.

c. Central grid point, which corresponds to the position of the tropical cyclone, was omitted from the training set data. Four distinct networks were trained based on the quadrant of past movement.

FORECAST TYPE	OVERALL ABILITY	FALSE STARTS	NON-PERSISTENT FORECASTS	PERSISTENCE
BP-P7	70	16	41	67
BP-P5	49	22	29	67
BP-P4	67	16	29	67
BP-P3	78	5	41	67
BP-P2	78	5	41	67
BP-U7	69	11	24	67
BP-U5	76	5	35	67
BP-U4	70	5	18	67
BP-U3	69	8	18	67
BP-U2	76	8	29	67
BP-V7	65	22	35	67
BP-V5	65	14	18	67
BP-V4	67	16	29	67
BP-V3	72	8	29	67
BP-V2	67	3	0	67

KEY TO FORECAST TYPE

BP- : results of forecasts issued by the pattern recognition technique, Back Propagation

FIELDS USED BY PATTERN RECOGNITION TECHNIQUES

-P# : geopotential height at #00 mb
-U# : u-component of the wind at #00 mb
-V# : v-component of the wind at #00 mb